Nuclear Effects on the Extraction of Neutron Structure Functions

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Abstract

Nuclear effects in light nuclei due to the presence of spin-one isosinglet 6-quark clusters are investigated. The quark distributions of 6-quark clusters are obtained by using a perturbative QCD (pQCD) based framework, which allows us to get a good description of the ratio of the deuteron structure function to the free nucleon structure function. Nuclear effects on the extraction of the neutron structure functions F_2^n and g_1^n are estimated. We find that the effect on the extracted spin-dependent neutron structure function is very different from that on the spin-independent neutron structure function. The effect enhances the Bjorken sum by about 10%, whereas its correction to the Gottfried sum is rather small. The formalism for calculating nuclear effects is further used to evaluate the spin-dependent structure function of the ^{3}He nucleus and a good self-consistent check is obtained.

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1 Introduction

It is well known that nuclear effects are commonly extracted from the analysis of structure functions ratios of different nuclei relative to the deuteron in the belief that they are negligible in this last system. On the other hand, some years ago the New Muon Collaboration(NMC) [1, 2] reported a value of the Gottfried sum, using the ratio $F_2^n/F_2^p = 2F_2^D/F_2^p - 1$, where nuclear effects in the deuteron target were neglected, and its structure function was regarded as the sum of the structure functions of the proton and neutron. Then the neutron structure function F_2^n can be extracted, and the ratio of the deuteron structure function F_2^D to the free nucleon structure function $F_2^N = (F_2^p + F_2^n)/2$ should read $R_F^{D/N} = 1$. However, Gomez et al. [3] found that the deuteron has a significant EMC effect [4], i.e. $R_F^{D/N} \neq 1$, especially in the region near $x \sim 0.6$. The analysis of Epele et al. [5] also shows a significant nuclear effect due to the composite nature of the deuteron. In fact, the importance of nuclear effects on the extraction of the neutron structure functions was recognized even much earlier [6]. Recent investigations of nuclear effects on a deuteron mainly emphasize the following three aspects: (1) the EMC effect on the spin-independent deuteron structure function [3, 7]; (2) the effects of Fermi motion of nucleons in the deuteron [8, 9, 10]; (3) depolarization of the nucleons and spin-dependent effects [11]. In recent work by Burov and Molochkov [7], the EMC effect on a deuteron is analyzed from a relativistic point of view. Fermi motion for the spin-independent F_2^D and F_3^D structure functions in light-cone variables was analyzed in Refs. [8] and [9], respectively. The same relativistic approach and a deuteron model have been used [10] in order to describe the effect of Fermi motion corrections to the spin-dependent structure function g_1^D, and to estimate nuclear effects in the $\mu + D \to \mu + X$ process. But there have been no detailed studies of the possible nuclear effects on the spin-dependent quark distributions themselves and the effects on the extraction of the neutron structure functions (F_2^n, g_1^n). Nuclear effects including Fermi motion and shadowing are very important in order to extract the neutron deep-inelastic structure functions from the experimental data for deuteron and heavy nuclei. They should be included into any QCD analysis of the nucleon structure

functions. The main purpose of our present work is to investigate nuclear effects on the extraction of the neutron structure functions.

Generally, it is hard to give a unified description of all nuclear effects including Fermi motion corrections at large x, and shadowing and anti-shadowing effects in the small x region. The work by Lassila and Sukhatme [12] shows that the quark cluster model (QCM) can be used to model the EMC effect over all x. The QCM has been successfully applied to inclusive electron deuteron reactions at large momentum transfer, and to nuclear Drell-Yan processes. Spin-dependent effects in the quark-cluster model of the deuteron and ^{3}He were investigated by Benesh and Vary [11]. However, in Ref. [11] there were no detailed 6-quark clusters quark distributions, and hence only the first moment of a particular distribution was involved in the estimation. In order to get more precise information of nuclear effects on the extraction of the neutron structure functions, detailed quark distributions of 6-quark clusters are necessary. This motivates us to construct the quark distributions of 6-quark clusters. Several years ago, Brodsky, Burkardt and Schmidt provided a reasonable description of the spin-dependent quark distributions of the nucleon in a pQCD based model [13]. This model has also been successfully used in order to explain the large single-spin asymmetries found in semi-inclusive pion production in pp collisions, while other models have not been able to fit the data [14]. Recently it has been also applied to obtain a good description of the spin and flavor structure of octet baryons [15], specially the Λ particle [16, 17, 18]. In this paper, we extend this analysis to 6-quark clusters, trying to describe its spin-dependent quark distributions in this framework.

The spin-dependent structure functions are interesting not only because they introduce a new physical variable with which to explore the detailed structure of the nucleon, but also because they provide a precise test of QCD via the Bjorken sum rule, which is a strict QCD prediction. In this paper, we will investigate nuclear effects on the extraction of the spin-dependent neutron structure function by considering the nuclear effects in the deuteron. We will see that nuclear effects cause a big enhancement of the Bjorken sum by about 10%, giving a final result which is much closer to the theoretical value of the Bjorken sum rule.

The paper is organized as follows. In section 2 we will describe the quark distri-

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butions of a 6-quark cluster in the pQCD based model. In section 3 we estimate the nuclear effects due to the presence of 6-quark clusters in the deuteron, and on the corresponding extraction of the spin-independent neutron structure function F_2^n. The ratio of the deuteron structure function to the free nucleon structure function and the effect on the Gottfried sum are calculated. We find that our model can give a very good unified description of the nuclear effects in the deuteron structure function and that the effect on the Gottfried sum is very small. In section 4 we present an analysis of the possible effect on the extraction of the spin-dependent neutron structure function and the Bjorken sum. A significant effect on the spin-dependent neutron structure function, and therefore on the Bjorken sum, is obtained. The formalism for calculation the nuclear effect is checked by applying it to the ^{3}He nucleus. Finally, a discussion and summary are included in section 5.

2 Quark Distributions in Spin-One Isosinglet 6-Quark Cluster

In order to describe the spin-dependent quark distributions of the nucleon, Brodsky, Burkardt and Schmidt developed a pQCD based model [13]. Here we extend this analysis to the description of the quark distributions in a 6-quark cluster. In the region $z \to 1$, where z is the light-cone momentum fraction carried by a given quark or antiquark in the 6-quark cluster ($0 \le z \le 1$), pQCD can give rigorous predictions for the behavior of distribution functions. In particular, it predicts "helicity retention", which means that the helicity of a valence quark will match that of the parent quark cluster. Explicitly the quark distributions of a spin-one isosinglet 6-quark cluster satisfy the counting rule [19],

$$Q_6(z) \sim (1-z)^p, \tag{1}$$

where

$$p = 2n - 1 + 2\Delta S_z. \tag{2}$$

Here n is the minimal number of the spectator quarks, and $\Delta S_z = |S_z^q - S_z^6| = 1/2$ or $3/2$ for parallel or anti-parallel quark and the 6-quark cluster helicities, respectively. More specifically, spin distributions for the non-strange quarks in the 6-quark cluster can be parameterized as,

$$Q_6^\uparrow(z) = \frac{1}{z^\alpha}[A_6(1-z)^{10} + B_6(1-z)^{11}], \tag{3}$$

$$Q_6^\downarrow(z) = \frac{1}{z^\alpha}[C_6(1-z)^{12} + D_6(1-z)^{13}]. \tag{4}$$

Here the distributions include both the quark and anti-quark contributions, i.e. $Q = q + \overline{q}$, and q is regarded as the sum of the non-strange quarks, i.e. $q = u + d$, since there are no detailed experimental data guiding us to determine separate quark distributions in the 6-quark cluster. The effective QCD Pomeron intercept $\alpha = 1.12$ is introduced to reflect the Regge behavior at low z and is chosen to have the same value as that for the nucleon [13]. There are 4 parameters for the above quark distributions. In consideration of the limiting case in which the spin-independent and spin-dependent structure functions of the 6-quark cluster become $F_2^6 = (F_2^p + F_2^n)$ and $g_1^6 = (g_1^p + g_1^n)$ respectively, we make the assumption that the value of the helicity carried by the quarks in the 6-quark cluster is twice as large as that in the nucleon. With this assumption, the first moment of the spin-dependent structure function of the 6-quark cluster is compatible with that obtained by s-wave MIT bag wave functions [11]. Therefore we fix the parameters by using the following conditions: one condition arises from the requirement that the sum rules converge at $z \to 0$; the second condition from the values of the integral of the polarized quark distribution $\Delta Q_6 = 0.68$ which is $2(\Delta u + \Delta d)$ of the nucleon [20]; the third condition reflects the fact that the momentum fraction z_Q carried by the quark and anti-quark of a 6-quark cluster should be half of that for a single nucleon, i.e., $z_Q = \frac{1}{2}(x_u + x_d) = 0.2605$ [21]. This leaves us with one unknown, which is chosen to be C_6. The three constraints give the solution set

$$A_6 = 1.0203C_6 + 3.3455,$$
$$B_6 = -1.0954C_6 - 2.3519, \tag{5}$$
$$D_6 = -1.0751C_6 + 0.9936.$$

The probabilistic interpretation of parton distributions $Q_6^\uparrow$ and $Q_6^\downarrow$ implies the bounds

$$0 < C_6 < 13.225. \tag{6}$$

Similarly, the strange quark and antiquark distributions are parameterized as

$$S_6^\uparrow(z) = \frac{1}{z^\alpha}[A_s(1-z)^{12} + B_s(1-z)^{13}], \tag{7}$$

$$S_6^\downarrow(z) = \frac{1}{z^\alpha}[C_s(1-z)^{14} + D_s(1-z)^{15}], \tag{8}$$

with

$$A_s = 1.0145C_s - 2.4230,$$
$$B_s = -1.0785C_s + 2.5966, \tag{9}$$
$$D_s = -1.0640C_s + 0.1736,$$

which are constrained by (1) the requirement that the sum rules converge at $z \to 0$; (2) the values of $\Delta S_6 = -0.24$, twice as large as the value $\Delta S = -0.12$ for the nucleon [20]; (3) the sum of momentum fractions carried by the strange quarks and antiquarks, $z_s = 0.0175$, half of the value $x_s = 0.035$ for the nucleon [13]. The probabilistic interpretation of parton distributions $S_6^\uparrow$ and $S_6^\downarrow$ requires

$$2.389 < C_s < 2.713. \tag{10}$$

In the following calculation, first we consider only the contributions of non-strange quarks and determine the value $C_6 = 9.5$ by fitting the data of the ratio of the deuteron structure function to the free nucleon structure function. Then we investigate the effect due to the presence of the strange quark.

3 Nuclear Effects on Extraction of Spin-independent Neutron Structure Function

Nuclear effects on the extracted neutron structure function will be indicated by the ratio $R_F^{D/N}$ of the deuteron structure function to the free nucleon structure function, and the modification of the Gottfried sum.

3.1 Ratio $R_F^{D/N}$

The EMC effect indicates that there is overlap of nucleons and the existence of 6-quark clusters in a nucleus. Now we will use the above 6-quark cluster quark distributions in order to understand the nuclear effects in the deuteron structure function.

The probability for creating a 6-quark cluster in the deuteron has been calculated as $p_6 = 0.054$ [11]. We use a simple model where a fraction p_6 of the nucleons in deuterium have become part of a 6-quark cluster, with a fraction $(1 - p_6)$ remaining single nucleons. In order to compare with the experimental data, we introduce the ratio

$$R_F^{D/N} = \frac{F_2^D}{\tilde{F}_2^N}, \tag{11}$$

where

$$\tilde{F}_2^N = \frac{1}{2}(F_2^p + \tilde{F}_2^n), \tag{12}$$

with

$$\tilde{F}_2^n(x) = \frac{\left[2F_2^D(x) - p_6\tilde{F}_2^6\left(\frac{x}{2}\right)\right]}{1 - p_6} - F_2^p(x), \tag{13}$$

assuming that the clusters formed in the s-wave and d-wave components have the same structure. We denote the neutron structure function as $\tilde{F}_2^n$, which is different from F_2^n, extracted via

$$F_2^n(x) = 2F_2^D(x) - F_2^p(x), \tag{14}$$

without considering nuclear effects. In (13), the structure function of the 6-quark cluster can be expressed as

$$\tilde{F}_2^6(z) = \frac{z}{9}[5Q_6(z) + 2S_6(z)], \tag{15}$$

where

$$Q_6(z) = Q_6^{\uparrow}(z) + Q_6^{\downarrow}(z), \tag{16}$$

and

$$S_6(z) = S_6^{\uparrow}(z) + S_6^{\downarrow}(z). \tag{17}$$

In Eqs. (13) and (14), the deuteron structure function F_2^D and the proton structure function F_2^p are take from the parametrizations of NMC [22]. Our numerical calculations show that the effect of the strange quark is very small. In order to understand the data of $R_F^{D/N}$ at $Q^2 = 4 GeV^2$, the one free parameter for the non-strange quark distribution Q_6 of the 6-quark cluster should be chosen as $C_6 = 9.5$. In Fig. 1 we present the calculated results of the ratio $R_F^{D/N}$, together with the data which were extracted by Gomez et al. [3] using a model of Frankfurt and Strikman [23]. We obtain a good unified description of the nuclear effects including shadowing, anti-shadowing at small x and Fermi motion at large x, with the presence of 6-quark clusters. It has been commonly accepted that the overlap of the nucleons in nuclei can result in the nuclear shadowing due to the parton recombination at small x [24, 25, 26]. The quarks in a 6-quark cluster have a larger confinement size than those in the nucleon, which leads to the re-distribution of the quarks towards to the lower momentum end, i.e. lower x region according to the uncertainty principle. This causes a suppression of the quark distributions in the medium x region and an enhancement in the low x region. The competition of the enhancement effect with the shadowing effect leads to the anti-shadowing effect at $x \sim 0.1$. A rise of the ratio at large x is expected from Fermi motion of the nucleons, and this is related to the nuclear wave function for overlapping nucleons which is here modeled as a 6-quark cluster. The nuclear effects over all x have been unified modeled as the presence of the 6-quark clusters in the deuteron. The strange quark in the 6-quark clusters only gives very small modification, and there is no significant change in its effect when the free parameter C_s

varies in the admissible range [2.389, 2.713]. For simplicity, we only show the strange contribution with $C_s = 2.4$ in the following results.
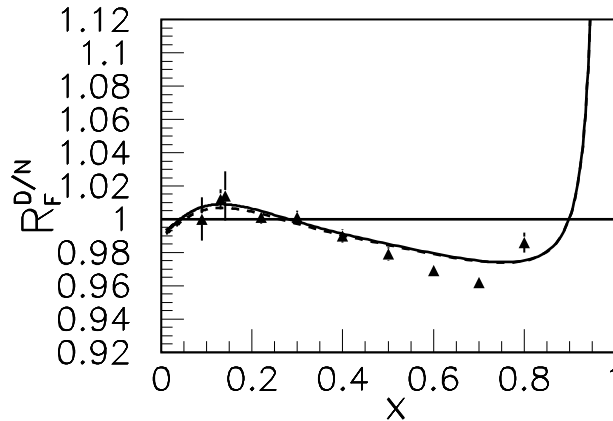

Figure 1: The ratio $R_F^{D/N}(x)$ and the comparison with the data from Ref. [3]. Dashed and solid curves correspond to including only contributions of non-strange quarks, and including also the contribution of the strange quark in the 6-quark cluster, respectively.

3.2 The Effect on the Gottfried Sum

Recently, the New Muon Collaboration (NMC) experiment [1] has provided values for the ratio of the structure function F_2^n/F_2^p, assuming that nuclear effects are not significant in the deuteron, i.e.,

$$F_2^p - F_2^n = 2F_2^D \frac{1 - F_2^n/F_2^p}{1 + F_2^n/F_2^p}, \tag{18}$$

where

$$\frac{F_2^n}{F_2^p} = 2\frac{F_2^D}{F_2^p} - 1. \tag{19}$$

The Gottfried sum is defined as [27]

$$S_{GS} = \int S_{GF}(x)dx, \tag{20}$$

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with the Gottfried integrand function given by

$$S_{GF}(x) = \frac{(F_2^p(x) - F_2^n(x))}{x}. \tag{21}$$

When we allow for the presence of 6-quark clusters in the deuteron, the neutron structure function should be extracted as $\tilde{F}_2^n$ from Eq. (13). The corresponding Gottfried integrand should be modified from S_{GF} to

$$\tilde{S}_{GF}(x) = \frac{(F_2^p(x) - \tilde{F}_2^n(x))}{x}. \tag{22}$$

In order to visualize the nuclear effects, the ratio

$$R_{GF}(x) = \frac{\tilde{S}_{GF}(x)}{S_{GF}(x)} \tag{23}$$

is shown in Fig. 2. Taking the minimal value of x as $x_{min} = 0.004$, which corresponds to the kinematic limit of the experiment in Ref. [2], we obtain the value of the Gottfried sum,

$$S_{GS} = \int_{0.004}^{1} S_{GF}(x)dx = 0.226, \tag{24}$$

and

$$\tilde{S}_{GS} = \int_{0.004}^{1} \tilde{S}_{GF}(x)dx = 0.215, \tag{25}$$

without taking into account the contribution of the strange quarks in the 6-quark clusters. We find an approximate 5% suppression in the Gottfried sum due to nuclear effects. When the contribution of the strange quark is also included with $C_s = 2.4$, we find that the Gottfried sum becomes $\tilde{S}_{GS} = 0.221$, which is very close to the value of S_{GS}.

In addition, the ratio of the structure function of the neutron to that of the proton, as shown in Fig. 3, also indicates a weak modification of the extracted spin-independent neutron structure function due to nuclear effects. Therefore nuclear effects on the Gottfried sum are very small, although $R_{GF}(x)$ deviates obviously from unity as shown in Fig. 2. The $x \to 1$ behavior of the neutron to proton structure

function ratio is an important result which can differentiate between different nucleon structure models [28]. For example, in exact SU(6) its value is 2/3, in some diquark models it is 1/4 [29], while pQCD predicts 3/7 [30, 13]. Our analysis favors the pQCD prediction.
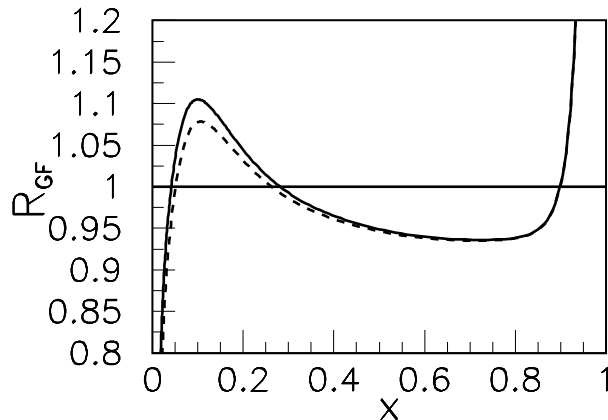

Figure 2: The ratio $R_{GF}(x)$. Dashed and solid curves correspond to including only contributions of non-strange quarks, and including also the contribution of the strange quark in 6-quark clusters, respectively.

4   Nuclear Effects on Extraction of Spin-dependent Neutron Structure Function

Similar to the spin-independent case, we will consider the same nuclear effects on the extraction of the neutron spin-dependent structure function. We will indicate these effects by presenting the result of the ratio $R_g^{D/N}$ of deuteron spin-dependent structure function to the free nucleon spin-dependent structure function, and the correction to the Bjorken sum.

4.1   Ratio $R_g^{D/N}$

In the absence of 6-quark clusters, only the depolarization of the proton and neutron in the d wave component of the deuteron wave function will be taken into account,
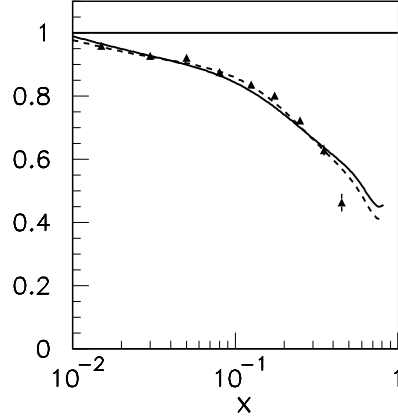
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Figure 3: The ratios F_2^n/F_2^p and $\tilde{F}_2^n/F_2^p$ are shown in dashed and solid curves, respectively. The neutron structure function is extracted from the deuteron structure function F_2^D and the proton structure F_2^p which are take from the parametrizations of NMC [22]. Experimental data are taken from Ref. [2].

and hence the spin-dependent structure function can be written as

$$g_1^D(x) = (p_s - \frac{1}{2}p_d)\frac{[g_1^p(x) + g_1^n(x)]}{2}, \tag{26}$$

where p_s and p_d denote the probabilities for finding the deuteron in an s or d wave, respectively. If we allow for the existence of 6-quark clusters in deuterium, $g_1^D(x)$ becomes [11]

$$g_1^D(x) = [(p_s - p_{6s}) - \frac{1}{2}(p_d - p_{6d})]\frac{[g_1^p(x) + \tilde{g}_1^n(x)]}{2} + \frac{1}{2}p_6 g_1^6(\frac{x}{2}), \tag{27}$$

where $p_{6s} = 0.047$ and $p_{6d} = 0.007$, the probabilities for creating a 6-quark cluster in the s and d states, were calculated by Benesh and Vary [11], $p_6 = p_{6s} + p_{6d}$, and g_1^6 is the spin-dependent structure function of a spin one, isosinglet 6-quark cluster,

$$g_1^6(z) = \frac{1}{18}[5\Delta Q_6(z) + 2\Delta S_6(z)]. \tag{28}$$

where

$$\Delta Q_6(z) = Q_6^\uparrow(z) - Q_6^\downarrow(z), \tag{29}$$

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and

$$\Delta S_6(z) = S_6^\uparrow(z) - S_6^\downarrow(z). \tag{30}$$

From Eqs. (26) and (27), both g_1^n, $\tilde{g}_1^n$ can be extracted, without 6-quark clusters and with 6-quark clusters, respectively. The first moment of the spin-dependent structure function of the 6-quark cluster reads

$$\overline{g}_1^6 = \int_0^1 g_1^6(z)dz = 0.189 \tag{31}$$

including only contributions of non-strange quarks. When the strange quark is also included, $\overline{g}_1^6$ becomes 0.162, which is compatible with that obtained by s-wave MIT bag wave functions[11].

Similar to the spin-independent case, the nuclear effect is described by the ratio

$$R_g^{D/N}(x) = g_1^D(x)/\tilde{g}_1^N(x) \tag{32}$$

and

$$\tilde{g}_1^N(x) = \frac{1}{2}[g_1^p(x) + \tilde{g}_1^n(x)] \tag{33}$$

In our numerical calculation, g_1^D is taken from a fit to the E155 data [31], and g_1^p from a fit to the E143 data [32]. The ratio $R_g^{D/N}$, as shown in Fig. 4, is very different from the ratio $R_F^{D/N}$ (see Fig. 1), and it is also very different from that obtained in Ref. [10], where only Fermi motion corrections were considered, and whose result is independent of x over a wide range of $x = 10^{-3} - 0.7$, with a value of 0.9.

4.2 The Effect on the Bjorken Sum

Now, we turn to investigate the nuclear effect on the Bjorken sum [33]. This sum is defined as

$$S_{BS} = \int S_{BF}(x)dx, \tag{34}$$
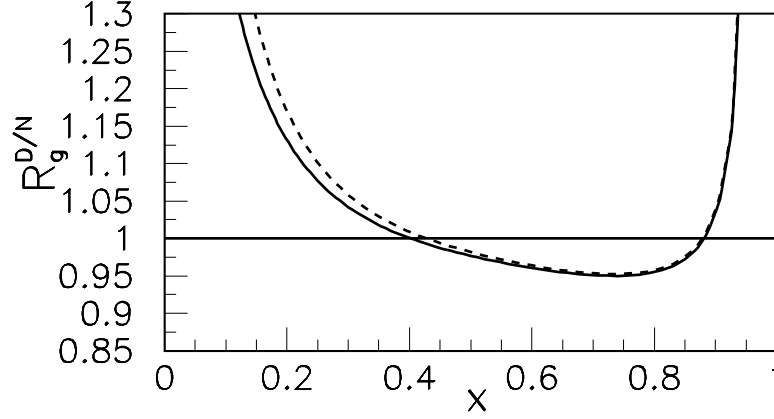
with the Bjorken integrand function

Figure 4: The ratio $R_g^{D/N}(x)$. Dashed and solid curves correspond to including only contributions of non-strange quarks, and including also the contribution of the strange quark in the 6-quark cluster, respectively.

$$S_{BF}(x) = g_1^p(x) - g_1^n(x). \tag{35}$$

There is also a Bjorken sum $\tilde{S}_{BS}$, and a Bjorken integrand function $\tilde{S}_{BF}(x)$, corresponding to the extracted $\tilde{g}_1^n$ which includes nuclear effects.

The Bjorken sum rule with perturbative QCD correction to first order of α_s reads

$$S_{BS}^{th} = \frac{1}{6} g_A [1 - \frac{\alpha_s(Q^2)}{\pi}]. \tag{36}$$

With the well measured neutron beta decay coupling constant $g_A = 1.2601 \pm 0.0025$ [34] and very recently determined QCD coupling α_s[35] at $Q^2 = 4 GeV^2$, one finds

$$S_{BS}^{th} \simeq 0.189. \tag{37}$$

In order to show the nuclear effect on the Bjorken integrand, we introduce the ratio

$$R_{BF}(x) = \frac{\tilde{S}_{BF}(x)}{S_{BF}(x)}, \tag{38}$$

whose value is larger than unity over the whole x region (see Fig. 5), therefore indicating an enhancement of the value of the Bjorken sum. Actually, the value of the

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sum changes from $S_{BS} = 0.166$ to $\tilde{S}_{BS} = 0.185$, with an increase of $\sim 11\%$ when only the contribution of non-strange quarks in the 6-quark cluster is considered. When the strange quark in the 6-quark cluster is further included with $C_s = 2.4$, the Bjorken sum result decreases to 0.182. This value is very close to the value in Eq. (37), the strict QCD prediction of the Bjorken sum rule. Therefore, the nuclear effect due to the presence of 6-quark cluster favors the case in which the Bjorken sum rule holds.
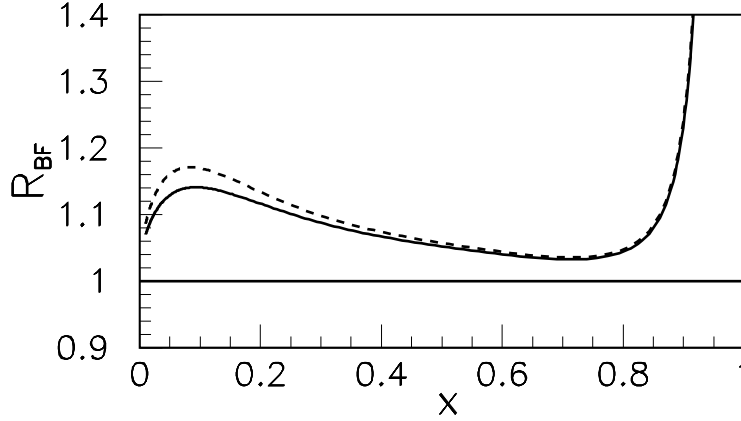

Figure 5: The ratio $R_{BF}(x)$. Dashed and solid curves correspond to including only contributions of non-strange quarks, and including also the contribution of the strange quark in the 6-quark cluster, respectively.

4.3 The Helium Spin-dependent Structure Function g_1^{He}

The ^{3}He nucleus is a suitable system in which to check the above formalism for calculating the nuclear effect. Recently, some measurements on g_1^n have been made by using deep inelastic scattering of polarized electrons on polarized ^{3}He [36, 37, 38]. In the simplest picture of ^{3}He, all nucleons are in an S wave, which consequently has a completely anti-symmetric spin-isospin wave function. The protons in ^{3}He are restricted by the Pauli principle to be in a spin-singlet state. It is usually believed that a polarized ^{3}He nucleus automatically provides a highly polarized neutron which is rather loosely bound. We can use ^{3}He to have a self-consistent check for the extracted neutron spin-dependent structure function. With the probabilities of 6-quark clusters in ^{3}He calculated by Benesh and Vary with the Bonn deuteron wave functions [11], we

assume that the change of the nuclear environment from Deuterium to Helium does not alter the quark spin structure of the 6-quark clusters and employ the extracted neutron spin-dependent structure function to predict the spin-dependent structure function of ^{3}He. In Fig. 6, the spin-dependent structure functions of the neutron and Helium are shown in (a) and (b) respectively, without the 6-quark clusters (dashed curve) and with the nuclear effect due to the presence of the 6-quark clusters (solid curve). We find that the calculated spin-dependent structure function of ^{3}He almost does not change, and therefore still provides a good fit to the experimental data (see Fig. 6(b)), although the neutron spin-dependent structure function has a significant modification (see Fig. 6(a)). The contribution to the spin-dependent structure function of ^{3}He from the correction of the neutron spin-dependent structure function is almost canceled by that from 6-quark clusters. It means that we can also extract the same neutron spin-dependent structure function from the experimental data of g_1^{He} with the existence of 6-quark clusters in Helium as that from g_1^D. This provides a good self-consistent check of our present framework.
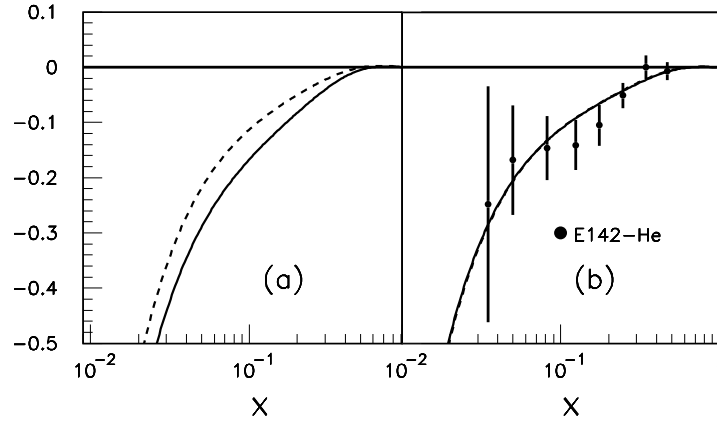

Figure 6: (a) $g_1^n(x)$ and $\tilde{g}_1^n(x)$; (b) $g_1^{\text{He}}(x)$ (dashed curve) and $\tilde{g}_1^{\text{He}}(x)$ (solid curve). The dashed and solid curves correspond to without considering the 6-quark clusters and including the nuclear effect due to 6-quark clusters, respectively. Note that the dashed and solid curves in (b) almost overlap. The experimental data are taken from the E142 [38].

5 Discussion and Summary

For simplicity, only 6-quark clusters have been included in our approach. Inclusion of 9-quark clusters causes the maximum at $x \simeq 0.1$ to shift a little bit in Fig. 1. The calculations by Sato [39] show that the probability for forming 9-quark clusters increases with the nuclear mass number A. In our present discussion of light nuclei, they can be neglected.

In our numerical calculation, $Q^2 = 4GeV^2$ was chosen in order to compare the results of the Gottfried sum with the experimental data of NMC [1]. This is also consistent with the kinematic range of the experiment in which the ratio $R_F^{D/N}(x)$ was extracted [3]. In principle the present simple analytic representations of the quark distributions in 6-quark clusters only reflect the intrinsic bound-state structure of the 6-quark clusters and they are valid at low Q^2 where QCD evolution can be neglected. At high Q^2, the radiation from the struck quark line increases the effective power-law fall-off $(1-x)^p$ of the structure functions relative to the underlying quark distributions: $\Delta p = (4C_F/\beta_1)\log[\log(Q^2/\Lambda^2)/\log(Q_0^2/\Lambda^2)]$ [13], where $C_F = 4/3$ and $\beta_1 = 11 - \frac{2}{3}n_f$. With this estimate, the effect due to the scale change from $Q_0^2 = 1GeV^2$ to $Q^2 = 4GeV^2$ on our analysis is small. The quark distributions of the 6-quark cluster can be used as the input distribution for perturbative QCD evolution from Q_0^2 to a higher resolution scale.

To sum up, we investigated the nuclear effects in light nuclei due the presence of 6-quark clusters. The quark distributions of the 6-quark clusters were modeled in the pQCD based framework. With the presence of the 6-quark clusters in the deuteron, the nuclear effects including shadowing, anti-shadowing and Fermi motion, which are described by the ratio of the deuteron structure function to the free nucleon structure function, can be well explained. The nuclear effects on the Gottfried sum are small. Then we extended the formalism for calculating the nuclear effects to the extraction of the spin-dependent neutron structure function. We find that the nuclear effect on the extraction of the spin-dependent neutron structure function is more significant than that on the spin-independent neutron structure function. The effect results in an increase in the Bjorken sum by about 10%, which favors the strict QCD prediction

of the Bjorken sum rule. A good self consistent check of the formalism for calculating the nuclear effects was provided by evaluating the spin-dependent structure function of the ^{3}He nucleus.

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